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Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review

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ABSTRACT

Iron and steel manufacturing is among the most energy-intensive industries. Ironmaking accounts for the major share of total energy use in steel production in integrated steel mills that use blast furnaces and basic oxygen furnace. Although studies from around the world have identified a wide range of energy-efficiency technologies applicable to the ironmaking process that have already been commercialized, information is limited and/or scattered regarding alternative emerging or advanced energy-efficiency and low-carbon technologies that are not yet fully commercialized. This paper consolidates available information on 12 alternative emerging ironmaking technologies, with the intent of providing a well-structured database of information on these technologies for engineers, researchers, investors, steel companies, policy makers, and other interested parties. For each technology included, we provide information on energy savings and environmental and other benefits, costs, and commercialization status. All the alternative emerging ironmaking technologies eliminate energy-intensive coke production. COREX® Process, FINEX® Process, and Coal-Based HYL Process are very promising alternative emerging ironmaking technologies because they are already commercialized, but they have very low adoption rate in the steel industry worldwide.

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1. Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, use of coal as the primary fuel for iron and steel production means that iron and steel production has among the highest carbon dioxide (CO_2) emissions of any industry. According to the International Energy Agency (IEA), the iron and steel industry accounts for the largest share – approximately 27 percent – of CO_2 emissions from the global manufacturing sector [1].

Annual world steel demand is expected to grow from approximately 1410 million tonnes (Mt) of crude steel in 2010 [2] to approximately 2200 Mt in 2050 [3]. The bulk of this growth will take place in China, India, and other developing countries in Asia (Fig. 1). This significant increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO_2 emissions.

Studies have documented the potential for the worldwide iron and steel industry to save energy by adopting commercially available energy-efficiency technologies and measures [1,4–5]. However, in view of the projected continuing increase in absolute steel production, future reductions (e.g., by 2030 or 2050) in absolute energy use and CO_2 emissions will require innovation beyond technologies that are available today. New developments will likely include alternative ironmaking processes that can economically reduce energy use and CO_2 emissions. Deployment of these new technologies in the market will be critical to the industry's climate change mitigation strategies for the mid and long term. It should be noted that the ttechnology adoption in regions around the world is driven by economic viability, raw materials availability, energy type used and energy cost as well as regulatory regime.

Many studies from around the world have identified sector-specific [6–10] and cross-cutting [11] energy-efficiency technologies for the iron and steel industry that are already commercially available. However, information is limited and not easily accessible regarding emerging or advanced energy-efficiency and low-carbon technologies for the industry that have not yet been commercialized. Since ironmaking consumes highest share of the energy in the steel production from iron ore, this paper consolidates the available information on alternative emerging ironmaking technologies to assist engineers, researchers, investors, iron and steel companies, policy makers, and other interested parties. The paper aims to contribute to energy efficiency, CO_2 and other air pollutants emissions reduction and sustainability in the steel industry by filling the gap in the information.

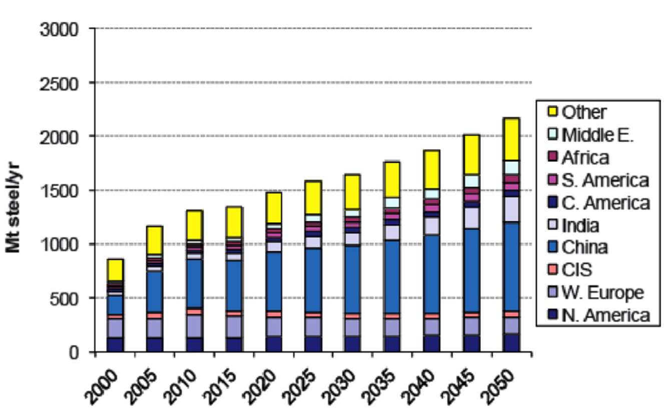


Fig. 1. World steel consumption by region [3].

The information presented in this paper is collected from publically available sources [1–43] and covers the main alternative emerging ironmaking technologies; however, the list of emerging technologies addressed is not exhaustive.

The paper uses a uniform structure to present information about each of the 12 technologies covered. First, we describe the technology, including background, theory, pros and cons, barriers and challenges, and case studies if available. Next, we present the energy, environmental, and other benefits of the technology as well as cost information if available. For most technologies, we include a block diagram or picture. Finally, we identify the commercialization status of each technology. The commercialization status of each technology is as of the writing of this paper and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: The technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

The purpose of this paper is solely informational. Many emerging technologies are proprietary and/or the manufacturers who are developing a new technology are the primary sources of information about it. Thus, in some cases, we identify a company that is the source of a technology so that readers can obtain more information about the company and product. Because the nature of emerging technologies is continual and often rapid change, the information presented in this paper is also subject to change.

2. Description of iron and steel production

Iron ore is chemically reduced to produce steel by one of these three process routes: blast furnace (BF)/basic oxygen furnace (BOF), smelting reduction, or direct reduction [9]. Steel is also produced by direct melting of scrap in an electric arc furnace (EAF). Each of these processes are briefly explained in the section below.

BF/BOF and EAF production are the most common today. In 2010, BF/BOF production accounted for approximately 65 percent of the steel manufactured worldwide, and EAF production accounted for approximately 30 percent [43]. Iron and steel can be produced at separate facilities or in an integrated steel mill, where the iron ore is reduced into pig iron or DRI (direct reduced iron) and then processed into steel at the same site.

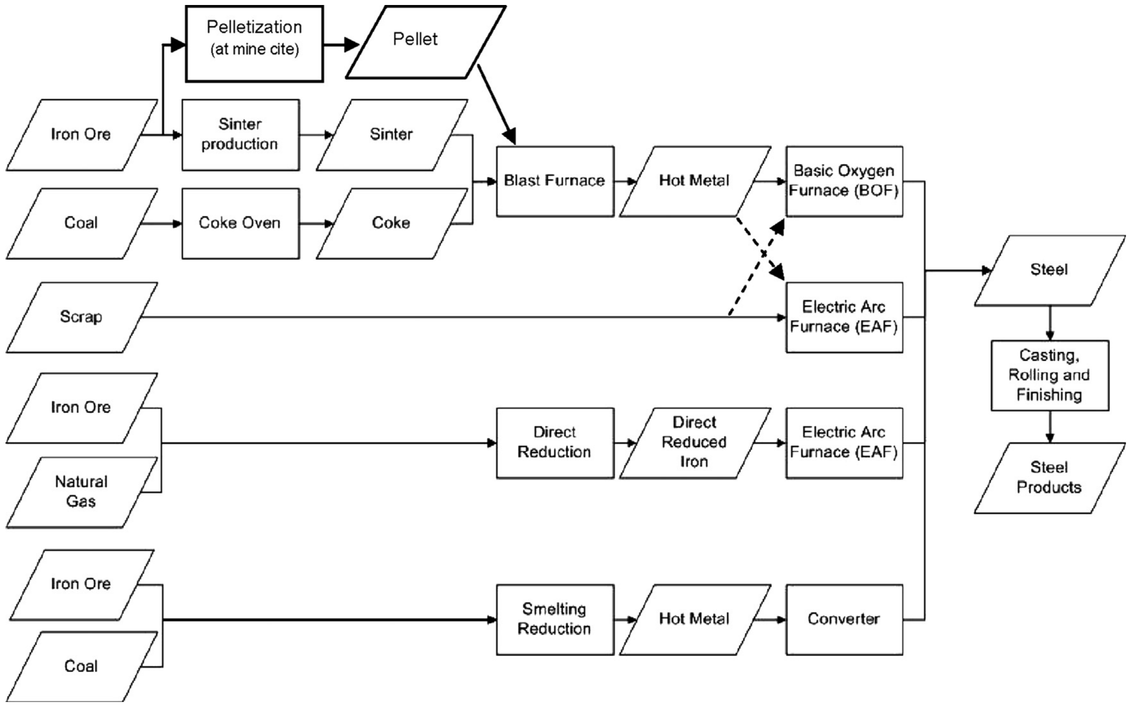


Fig. 2. Flow diagram of steel production.

2.1. Ironmaking production processes

Fig. 2 is a simplified flow diagram of steel production using BF/BOF, EAF, and direct reduction. The following subsections describe the main production steps. Since the focus of this paper is ironmaking, in this section we only briefly describe three ironmaking processes, i.e. the BF, direct reduction, and smelting reduction processes.

2.2. Blast furnace

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal.[1] Hot metal is a solution of molten iron at approximately 1480 °C, which contains 4 percent carbon and some Silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically “tapped” from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF/BOF steelmaking process, generating large quantities of CO_2 [7]. Energetics, Inc. gives a range of energy use of 13.0–14.1 GJ/t pig iron [21].

2.3. Direct reduction

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, 92.6 percent of direct reduction worldwide was based on natural gas and took place in shaft furnaces, retorts, and fluidized bed reactors. The metallization rate of the end product, called Direct Reduced Iron (DRI) or ‘sponge iron’, ranges from 85 percent to 95 percent (often even higher). In 2008, 68.5 Mt of DRI was produced worldwide, using primarily MIDREX technology (58.2 percent). The MIDREX process typically consists of four stages: (1) reduction, (2) reforming, (3) heat recovery, and (4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO [25]. The iron is then formed into briquettes, and heat from the process is recovered.

2.4. Smelting reduction

Smelting reduction iron (SRI) is an alternative to the BF, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products-coke and sinter (if sinter is used in BF). Instead smelting reduction is aimed to use coal and iron fines. Several processes are under development; some have been commercially proven (COREX, FINEX, ITmk3), others are under demonstration (e.g. Hismelt). Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage – similar to DRI – is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidized to generate additional heat to smelt the iron. Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting [25]. Commercial smelting reduction is still dominated by first-generation processes, notably the COREX process developed in Germany and Austria [25].

[1] When hot metal is allowed to solidify in a pig iron casting machine, the resultant solid iron is called pig iron.

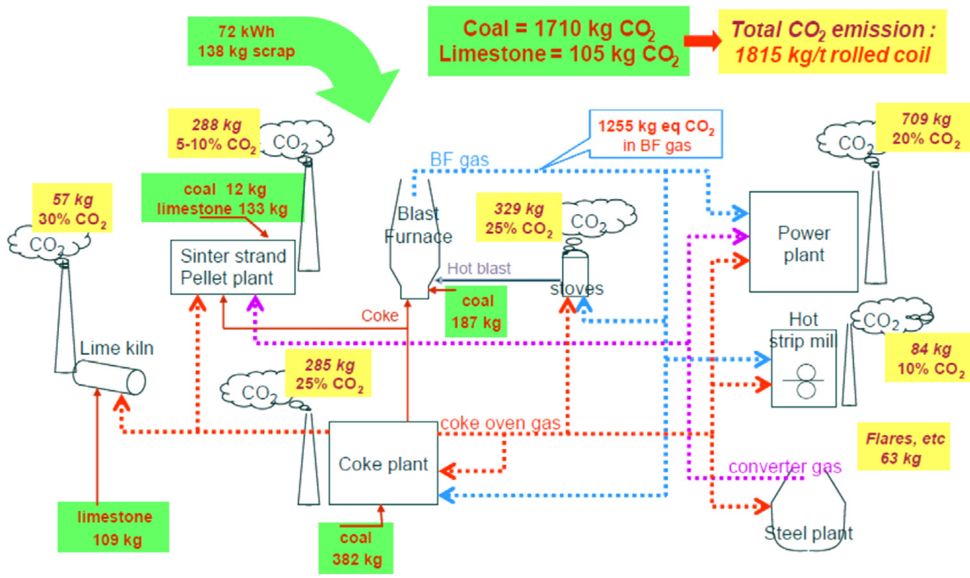


Fig. 3. CO_2 emissions from typical steel mill [17].

2.5. CO_2 impact of iron and steel production

Iron and steel production generates CO_2 emissions as (1) process emissions, in which raw materials and combustion both may contribute to CO_2 emissions; (2) emissions from combustion sources alone; and (3) indirect emissions from consumption of electricity (primarily in EAFs and in finishing operations such as rolling mills at both integrated steel plants and EAF plants) [10].

The major process units at iron and steel facilities where raw materials, usually in combination with fuel combustion, contribute to CO_2 emissions include the sinter plant, non-recovery coke oven battery combustion stack, coke pushing, BF exhaust, BOF exhaust, and EAF exhaust [10]. The primary combustion sources of CO_2 include: byproduct recovery coke oven battery combustion stack, BF stove, boiler, process heater, reheat furnace, flame-suppression system, annealing furnace, flare; ladle reheater, and other miscellaneous [10].

Fig. 3 shows the profile of CO_2 emissions from and material flow in a typical BF/BOF integrated steel plant. It shows that total CO_2 emissions of a typical integrated steel plant are equal to 1.8 tCO_2/t rolled coil, of which 1.7 tCO_2/t rolled coil is associated with coal use, and the other 0.1 tCO_2/t rolled coil is related to lime use [17].

3. Alternative emerging ironmaking technologies

The subsections below describe the following alternative iron-making processes that reduce energy use and carbon emissions: the COREX process, the FINEX process, Tecnored, ITmk3, the paired straight hearth furnace, the coal-based HYL process, the coal-based MIDREX process,[2] molten oxide electrolysis, suspension hydrogen reduction, fine ore reduction in a circulating fluidized bed, charging carbon composite agglomerates, use of biomass and waste oxides, and the cyclone converter furnace.

3.1. COREX® process

COREX® is an industrially and commercially proven SR process that allows for production of hot metal directly from iron ore and non-coking coal. The process was developed to industrial scale by Siemens VAI. COREX differs from BF production in using non-coking coal as reducing agent and energy source. In addition, iron ore can be directly charged to the process in form of lump ore, pellets, and sinter [34].

The COREX process is a two-stage direct smelting process, consisting of: (1) a melter-gasifier, which melts the DRI and gasifies the coal; and (2) a DRI shaft furnace mounted above melter-gasifier, which reduces lump ore or pellets to DRI by reducing gas from the melter-gasifier. The shaft furnace is a modified MIDREX DRI counter-current reactor without a cooling zone in which lump ore or/and pellets are reduced to approximately 85-percent metallization. The hot DRI at a temperature of approximately 800 °C is discharged from the shaft furnace by means of horizontal screw conveyors, to the charging pipes of the melter-gasifier. The reducing gas enters the bottom of metallization zone. The fresh reducing gas from the melter-gasifier enters the shaft furnace at approximatelys 800 °C and then exits from the furnace top at ~450 °C. The melter-gasifier, which completes the reduction and melting of the DRI, consists of a fluidized bed chamber resting on liquid slag and a hot metal bath. Coarse coal is charged to the top of melter-gasifier and charred in the fluidized bed. Oxygen is injected via tuyeres around the circumference of the melter-gasifier. This forms a raceway in which the oxygen reacts with charred coal to form CO. For optimum energy efficiency and economics, the process requires the following auxiliaries: (1) CO_2 stripping of the shaft top gas, which enables better utilization of the process gas (after CO_2 stripping, the rich reducing gas could be recirculated to the shaft furnace); and (2) In most cases, co-generation of the export gas, required because of the high calorific value of the gas. An additional DRI shaft furnace could be also installed to utilize the off gas and to produce an amount of DRI equivalent to the hot metal from the melter-gasifier [8].

Some of the limitations of the COREX process are [12]:

- It cannot use ore fines directly
- There are restrictions on non-coking coal (volatile matter of carbonaceous material to be maintained at around 25 percent
- Net export gas should be utilized very economically, otherwise the process becomes un-viable.

There are five commercial COREX units in operation in China, Korea, India, and South Africa [34]. Fig. 4 is a simplified diagram of the COREX process.The following benefits are reported for COREX compared to a conventional BF [8,34]:

[2] Natural gas-based HYL and MIDREX processes are commercialized; thus, they are not included in this section as emerging technologies.

- No need for coking coal and coke.
- Fuel savings of 18 percent and oxygen consumption reduction of 13 percent (reported for a low-export gas system demonstration in India).
- Approximately 20-percent lower CO_2 emissions per t of product.
- Approximately 30-percent lower NO*x* emissions per t of product.
- No VOC emissions; significantly lower SO*x* emissions.
- Fuel rate significantly reduced by circulation of the shaft furnace top gas back to the shaft furnace.
- Reduced investment and operation costs.
- Lower slag production (18-percent slag production reduction reported in a low-export gas system demonstration in India).

Commercial status: Commercial with very low adoption rate

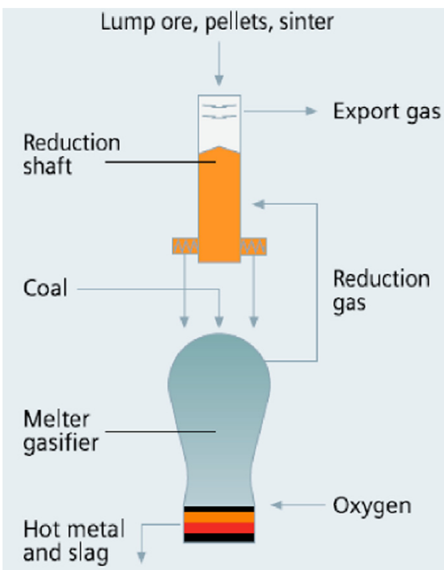


Fig. 4. Simplified flow diagram of the COREX process [34].

3.2. FINEX® process

The FINEX® smelting-reduction process, developed by Siemens VAI and the Korean steel producer Posco, is based on the direct use of non-coking coal and fine ore. The major difference between the COREX and FINEX processes is that the FINEX process can directly use sinter feed iron ore (up to 0.012 m) [34], without agglomeration.

The FINEX core plant consists of a melter-gasifier and a series of successive fluidized bed reactors that form a counter-flow system in which ore fines are reduced in three or four stages to DRI. The upper reactor stage serves primarily as a preheating stage. In the succeeding stages, the iron ore is progressively reduced to fine DRI. The fine DRI is then compacted and charged in the form of hot compacted iron (HCI) into the melter-gasifier. The charged HCI is subsequently reduced to metallic iron and melted. The heat needed for the metallurgical reduction and melting is supplied by coal gasification with oxygen. The reduction gas, also produced by the coal gasification, is passed through the fluidized bed reactors. The FINEX export gas is a highly valuable product and can be further used for DRI/HBI production, electric energy generation, or heating. The hot metal and slag produced in the melter-gasifier is frequently tapped from the hearth, as is also done in BF or COREX® operation [34].

Currently the Posco COREX plant is part of the FINEX demonstration, with an annual hot metal capacity of 900,000 t/year. Based on good results at the FINEX demonstration plant, Posco decided in August 2004 to construct a 1.5-million-t/year industrial FINEX plant at Posco Pohang Works, Korea which was commissioned in 2007 [34]. Siemens VAI Metals Technologies received an order from Posco Engineering & Construction Co., Ltd. (Posco E&C), a subsidiary company of the Korean steel producer Pohang Iron and Steel Co. Ltd. (Posco), for engineering and the supply of proprietary equipment for a FINEX plant with capacity of 2-million-t/year which is scheduled to commission in mid-2013 [36].

Fig. 5 compares the BF, COREX, and FINEX processes. The following benefits are reported for COREX compared to BF production [8,34]

- No need for pelletizing, sintering, or agglomeration of iron-bearing materials.
- Allows use of fine concentrates.

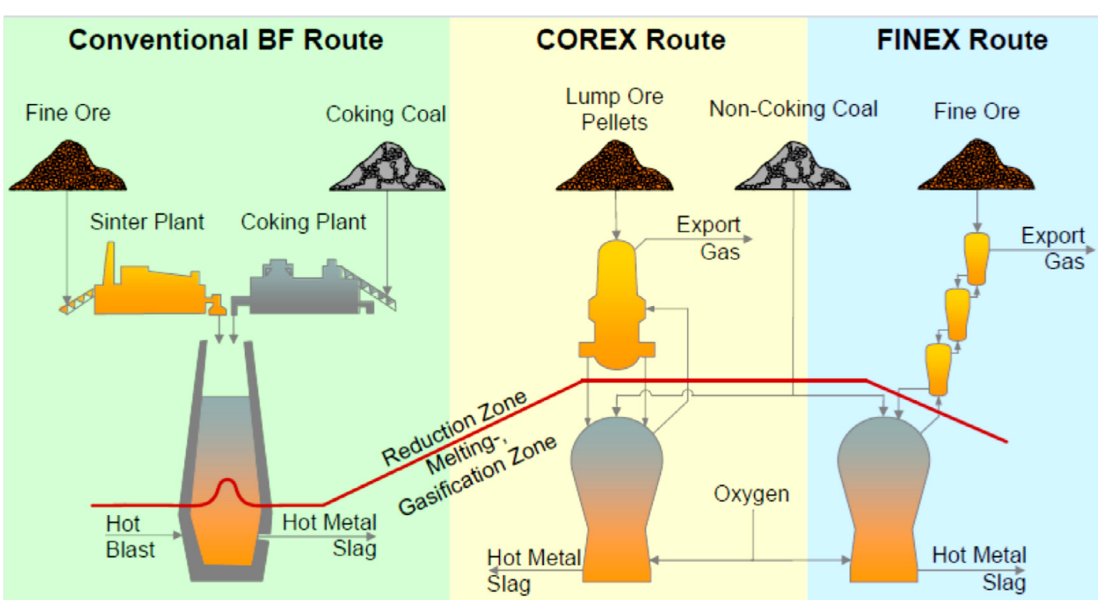


Fig. 5. Comparison of BF, COREX, and FINEX processes [24]: *Note*: This figure is primarily for illustration of major differences between three process. For the case of BF, however, in addition to sinter than is shown, the lump iron ore or sinter (or combinations) can be charged in BF.

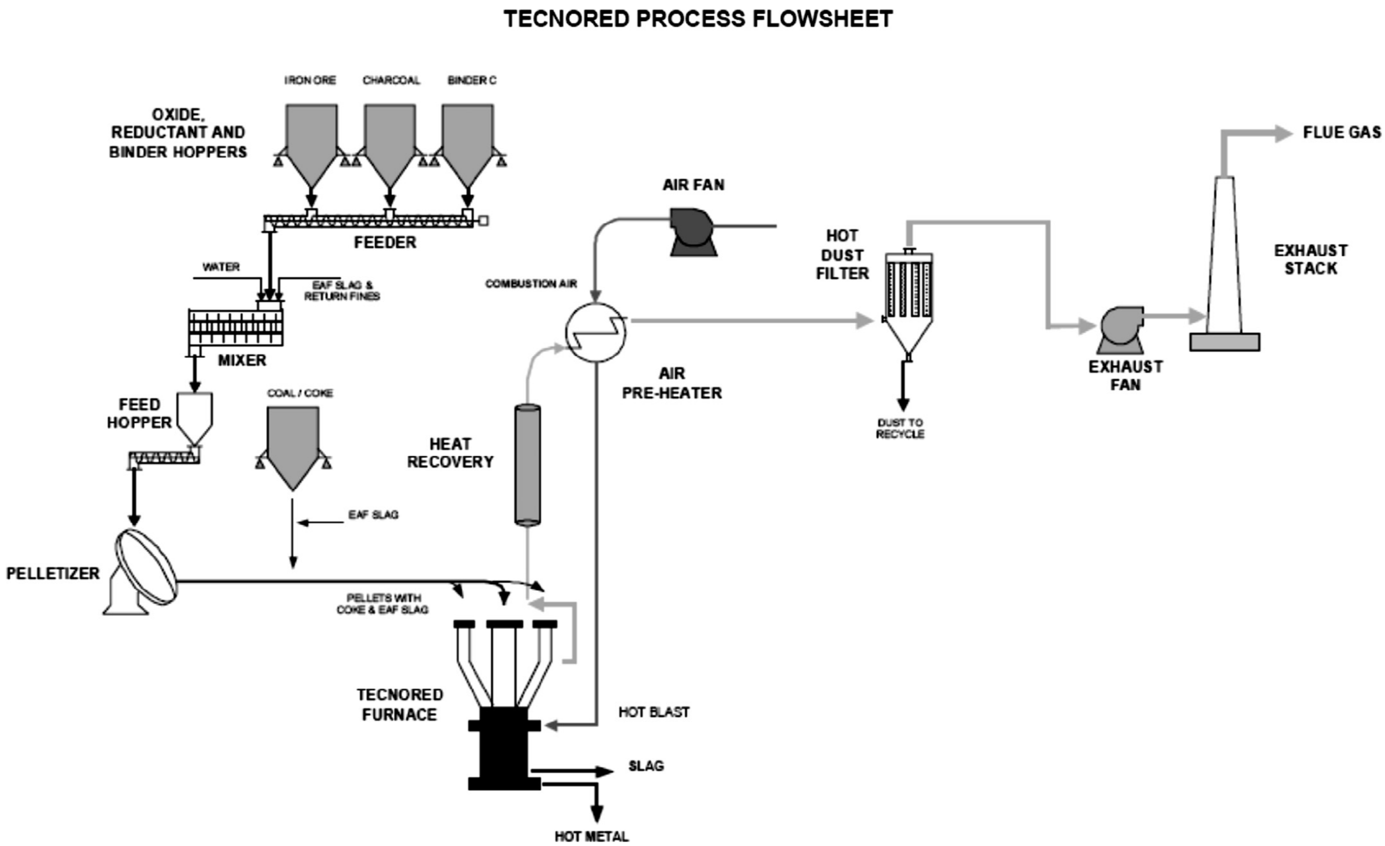


Fig. 6. Flow diagram of the Tecnored process [26].

- Capital cost claimed to be 20 percent lower than for BF, and production cost 15 percent lower.
- Lower emissions because of lower energy consumption and no need for coke making.
- Direct utilization of non-coking coal.
- High valuable export gas for a wide range of applications in metallurgical processes and energy production.
- Production of hot metal with quality similar to that produced in a BF.

Commercial status: Commercial with very low adoption rate.

3.3. *Tecnored*

The Tecnored process uses agglomerated pellets or briquettes containing iron ore fines and low-cost coals. Within the furnace, the pellets or briquettes are reduced to hot metal. Hot blast and other solid reductants are injected into the furnace as well. The furnace' shaft height is only 2–3 m and therefore much smaller than typical BFs [18].

The Tecnored process starts with preparation of self-reducing pellets or briquettes, which are made from iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines are mixed and agglomerated into pellets or briquettes. After a drying process, the pellets/briquettes are fed from the top to the Tecnored furnaces. Additional lump coal and hot blast are injected into the furnace as well. The top gas is cleaned. Some of the top gas is re-fed as cold blast to the furnace. Preheated top gas is either fed as hot blast to the furnace or is used for the drying of the self-reducing pellets/briquettes. Surplus top gas is exported, for example to co-generation system or to replace fuels in other processes. Hot metal and slag are tapped at the bottom of the furnace [18].

The Tecnored process can use low-cost materials (e.g., low grade iron ore fines, low-cost fuels). Its smaller design means it requires less power and less pressure within the furnace. It achieves full metallization (up to 99 percent). The process takes just 0.5 h compared to a typical blast furnace process, which takes up to 8 h. However, this technology needs further development, and its capacity is smaller than typical blast furnaces. A Vale Tecnored pilot plant reportedly started operating in 2011 in Brazil. The capacity of the test facility was intended to be 75,000 t with an increase to 300,000 t planned [16].

Fig. 6 shows a flow diagram of the Tecnored process. The following benefits are reported for the Tecnored process compared to conventional BF production [18,27]

- Eliminates the need to use coke and sintering facilities, thereby reducing construction costs, energy use, pollutants, and CO_2 emissions.
- Lower power and pressure requirements because of smaller size of furnace.
- Uses low-cost iron ore fines and low-cost fuels.
- Achieves full metallization (up to 99 percent).

Commercial status: Pilot stage.

3.4. *ITmk3® ironmaking process*

In almost all direct reduction ironmaking technologies that use a rotary hearth furnace (RHF), the RHF reduces iron ore to about 80 percent. A secondary smelting facility removes the remaining other material (gangue) from the ore. The DRI produced is usually taken to an EAF for final reduction and gangue removal. However,

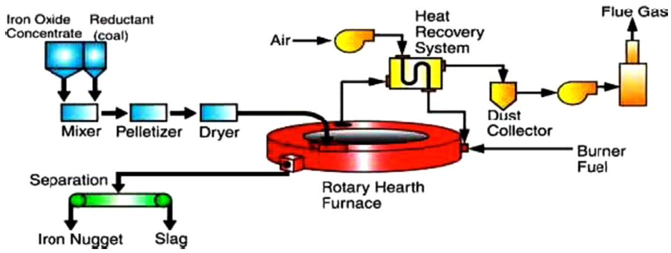


Fig. 7. ITmk3® process [8].

ITmk3® technology uses the RHF as a stand-alone unit that produces gangue-free metal eliminating the need for a secondary smelting process [22]. The ITmk3 process uses low-grade iron ore[3] and coal (other feedstocks can be used as supplements) to produce iron nuggets whose quality is superior to that of DRI (97 percent iron content) but is similar to that of pig iron. The mixing, agglomeration, and feeding steps are the same as in the production of DRI or BFs, but the RHF is operated differently. In the last zone of the RHF, the temperature is raised, which melts the reduced iron ore and enables it to separate easily from the gangue. The result is a nugget containing iron and carbon with almost no oxygen or slag [29]. This technology was demonstrated in a commercial scale demonstration plant co-funded by the U.S. DOE in 2006. This technology achieves reduction, melting, and slag removal in only about 0.15 h [41].

Kobe Steel, a Japanese steel company, developed and licensed the ITmk3 technology for production of nuggets. Mesabi Nugget, LCC, a joint venture between Steel Dynamics and Kobe Steel, began producing pig iron nuggets using ITmk3 technology in January 2010. The plant has the capacity to produce 500,000 t of nuggets per year. Mesabi Nugget produces iron nuggets principally as feedstock for EAF steelmaking [29]. Kobe Steel and SAIL (India's largest steel producing company) have signed an agreement to build the second ITmk3 plant with the capacity of 500,000 t in India [35].

Fig. 7 shows the ITmk3 process. Mesabi Nugget, LLC claims the following benefits for the ITmk3® technology compared to conventional steel making [29]

- Lower capital and operation costs.
- 30-percent energy savings over integrated steel making; 10 percent savings over EAF fed by DRI.
- No coke oven is required.
- Utilization of all chemical energy of coal; no gas exported from the system.
- Reduced NO*x*, sulfur oxide (SO*x*), and particulate matter emissions.
- Reduction, melting, and slag removal in only 0.15 h
- Reduction of iron oxide (FeO) to <2 percent, minimizing attack to refractories.

Commercial status: Demonstration stage.

3.5. Paired straight hearth furnace

The paired straight hearth (PSH) furnace is charged with cold-bonded self-reducing pellets composed of iron oxide and coal. When the pellets are heated, the iron oxide is chemically reduced to produce a 95-percent metallized pellet suitable for use in steelmaking in an EAF. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal. As the pellets are heated on the hearth, CO gas is evolved and combusted above the pellet bed to drive the process. The bed of conventional RHFs is only two to three pellets high whereas the PSH furnace has a bed height of eight pellets (approximately 120 mm). The PSH furnace off gases are fully combusted to raise the temperature above the bed to 1600 °C. Reoxidation is prevented by the CO-rich gases rising through the bed. The PSH furnace technology is significantly more productive while using less energy than conventional furnaces [7]. The initial research program, funded by the DOE/AISI TR Program, was completed in 2002.

In 2006, DOE/AISI, through its TR Program, commissioned an engineering study by a well-known furnace builder to verify the feasibility and costs of building a PSH furnace. The study concluded that it is feasible to design, build, and continuously operate a PSH furnace to produce 46,000 t per year of DRI at 95-percent metallization for a cost of $16,729,000. A detailed design and validation study to evaluate raw material flexibility was then initiated, and this study is scheduled to be completed in 2013. A demonstration-scale PSH furnace planned after that study is complete. The PSH furnace may be coupled to a smelter to provide a viable replacement for BF and BOF steelmaking.

Technology integration issues related to materials handling, furnace and waste treatment control systems, pellet quality, multi-layer bed stability, DRI quality, material throughput, process economics, long-term furnace performance, reliability, and stability are some of the barriers and uncertainties about this technology that need to be addressed [40]. The most likely point of initial entry for PSH furnaces into the mainstream market is integrated steelmaking facilities that might be looking for an alternative source of hot metal. This could include producers of coil, slab, long, or specialty steel products [40].

Fig. 8 shows the process flow in a PSH furnace. The following benefits are reported for PSH furnace ironmaking compared to BF ironmaking [8,40]:

- Higher-productivity smelting operations when used as a pre-reducer with a smelter, to the degree that the combined process is a suitable replacement for a BF/coke oven.
- 30 percent less energy at lower capital cost compared to BF ironmaking.
- One-third fewer total CO_2 emissions per t of hot metal produced.
- No coke oven is required.
- Coal used without requiring gasification.
- For EAF operations, reduced energy intensity because of availability of hot metal on site (reduced power consumption, tap-to-tap time).

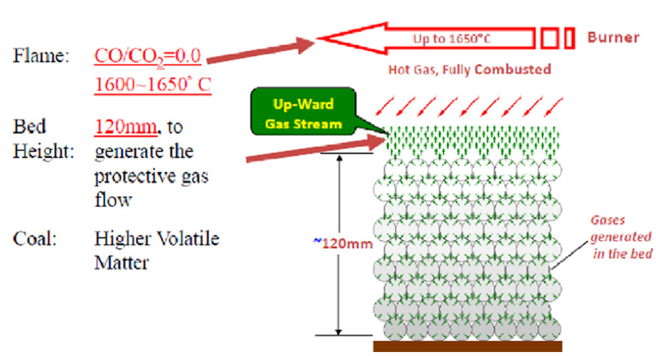


Fig. 8. Process flow of paired straight hearth furnace [28].

[3] This process does not use low grade ore directly. Low grade ores are beneficiated, and the resulting fines (with > 62% Fe content) are pelletized and used.

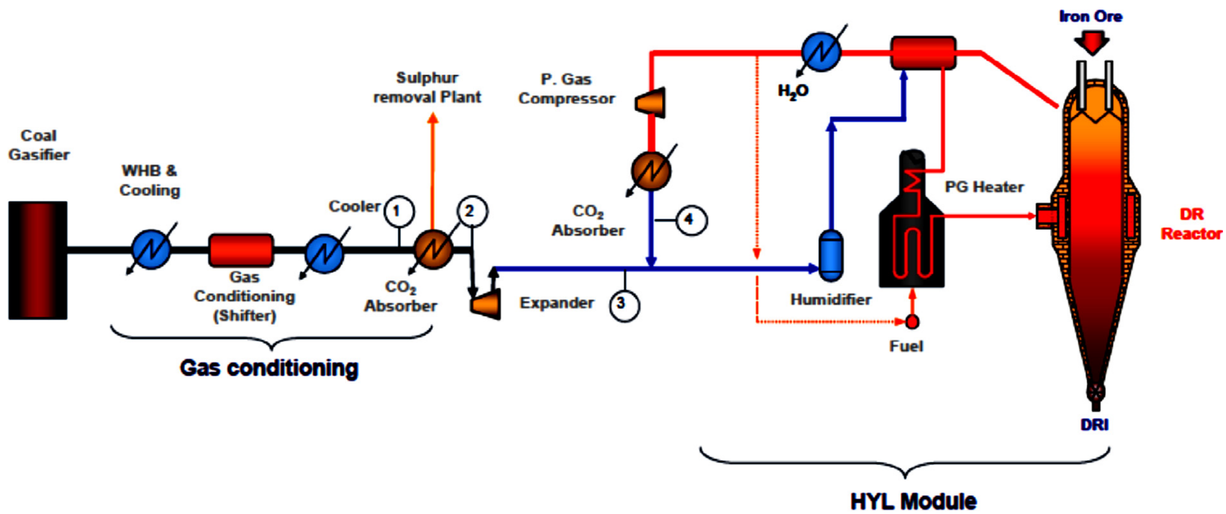


Fig. 9. Coal-based HYL Process [38].

- Reduced costs (no cokemaking process needed, high-volatility coals can be used).
- Can use high-volatility coals to produce DRI pellets from virgin iron ores and steelmaking waste products, an important advantage given the scarcity of high-quality raw material.

Commercial status: Development stage.

3.6. *Coal-based HYL process—a syngas-based DRI plant*

The HYL process, by Tenova HYL, is designed to directly reduce iron ores using reducing gases in a solid-gas moving bed reactor. Oxygen is removed from the iron ores by chemical reactions based on H_2 and CO to produce highly metallized DRI [19].

The original HYL technology used natural gas, but Tenova HYL has built a new coal-based HYL technology (also known as Energiron HYL technology) by adding a coal gasification technology to HYL. The reactor and its peripheral systems and the principles of operation for the coal-based HYL process are same as for the gas-based HYL process in which oxide material is fed from the top and is reduced by a counter-current flow of H_2 and CO containing gas. Because this process does not use natural gas, a lower-carbon-content product (around 0.4 percent) is expected. Similar to the gas-based HYL process, in the coal-based process, the furnace top gas is cooled and cleaned, and its CO_2 is removed and then recycled into a reducing gas circuit. Reducing gas is produced in a coal gasifier that can process practically any kind of carbon-bearing material. Coal and oxygen are injected into the gasifier, and almost all carbon in the coal is gasified. The gas is dust laden and includes CO_2 and H_2O as well as other impurities. It is cleaned and cooled in a series of cyclones and H_2O, CO_2, and sulfur are removed. Because the HYL reactor is designed to work with high-H_2-content reducing gas, and the gas from the gasifier contains considerable amounts of CO, a gas shift reactor is required to convert CO into H_2 by the reaction $CO+H_2O\rightarrow CO_2+H_2$. The shift reactor is installed before the CO_2 removal system. The temperature and pressure of the gas are then regulated before injection into the reactor [8].

Danieli & C. and Tenova HYL will build 4 units, each 2.75 million-t/year coal-based HYL plant for Jindal Steel and Power Limited in India. The Syngas plant will provide reducing gas for the DR plant as well as power generation facilities [37].

Fig. 9 diagrams the coal-based HYL process. Tenova HYL, Inc. claims the following benefits for coal-based HYL compared to BF production [8,38]

- No need for coking coal and coke.
- No need for natural gas.
- Allows usage of low-quality coals.
- Production of hot DRI that could be charged to EAF with significant energy savings.

Commercial status: Commercial with very low adoption rate.

3.7. *Coal-based MIDREX® process*

The MIDREX® direct reduction process uses a natural-gas-based shaft furnace process that converts iron oxides (pellets or lump ore) into DRI. The MIDREX direct reduction technology has evolved during the past four decades from plant capacities of just 150,000 t/year to capacities now approaching 2 million t/year [34]. This process currently produces 60 percent of the world's DRI annually [30]. However, because not all regions have abundant, inexpensive natural gas, another direct reduction alternative is needed. An alternative option is the MXCOL process, which uses synthetic gas (syngas) made from coal in combination with a MIDREX® direct reduction plant. Syngas options include a coal gasifier, coke oven gas, or BOF gas. The big advantage of coal gasification is that lower-grade, inexpensive domestic coals can be used to produce a high-quality reducing gas for the MIDREX shaft furnace [31].

The coal-based MXCOL/MIDREX reactor and auxiliary systems are the same as those for a gas-based MIDREX plant. In the MXCOL process, the cold syngas is depressurized to about 3 bar in a turbo expander, which generates electricity. The low-pressure syngas is mixed with recycled gas to produce the required reducing gas. The mixed gas is then heated to more than 9,00 °C and enters the shaft furnace where it reacts with the iron oxide to produce DRI. The spent reducing gas (top gas) exiting the shaft furnace is scrubbed and cooled, then passed through a CO_2 removal system, which reduces the CO_2 content to 2–3 percent or less. This ensures that the mixed reducing gas (syngas from the gasification plant and recycled top gas from the MIDREX plant) has an acceptably high reductant (H_2+CO) to oxidant (H_2O+CO_2) ratio for efficient iron oxide reduction. The CO_2 removal system will also remove the sulfur gases contained in the recycled top gas. The recycling of

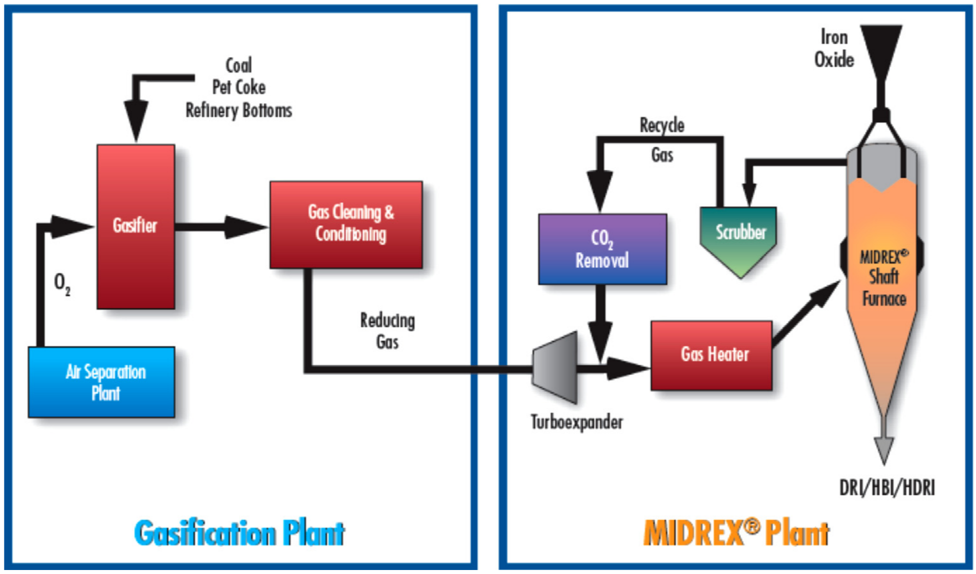


Fig. 10. Coal-based MIDREX Process [30].

the top gas makes MXCOL a very efficient process. Very pure CO_2 is recovered from the gasifier cleaning and conditioning plant and the CO_2 removal system in the MIDREX plant. These streams could be sequestered or sold for enhanced oil recovery or use in a petrochemical or other operation [31].

Jindal Steel and Power Limited in India has contracted with MIDREX Technologies for a 1.8 Mt/year MXCOL plant, the world's first coal gasifier-based MIDREX plant [31].

Fig. 10 shows a diagram of the coal-based MIDREX process. MIDREX Technologies, Inc. claims the ffollowing benefits for coal-based MIDREX compared to BF production [31]

- Can use any coal gasification technology (The additional cost of coal gasification should be taken into account.)
- Fixed-bed or fluidized-bed gasifier able to readily use the low-rank, high-ash domestic coals in India and China.
- Potential to use coal syngas from other sources such as coke oven gas or BOF gas.
- Uses the well-proven MIDREX direct reduction process; can readily use domestic iron oxides as feed material.
- Produces DRI with quality comparable to that produced by natural gas-based MIDREX plants.
- The DRI can be hot charged into a nearby EAF to significantly reduce the EAF electricity requirement and increase productivity.
- No coke, coke ovens, or sinter plant required.
- Lower specific capital cost than an integrated steel works.
- Lower air emissions than an integrated steel works.
- Ability to capture high-purity CO_2 for sequestering or injecting into oil and gas fields.

Commercial status: Demonstration stage.

3.8. Fine ore reduction in circulating and bubbling fluidized beds

Both Circored and Circofer are fine ore reduction processes. Circored is gas-based, and Circofer is coal-based. Both use a proven two-stage configuration, combining a circulating fluidized bed with a bubbling fluidized bed. Both are direct reduction processes utilizing iron ore fines directly to decrease DRI or HBI production costs by avoiding an expensive agglomeration step. The Circored process uses hydrogen as reductant. The first Circored plant, designed to produce 500,000 t/year of HBI, was commissioned in Trinidad in 1999. In the Circofer process, coal is used as reductant. The Circofer pilot plant at Outotec's research and development center in Frankfurt, Germany, has a capacity of 5 tpd ore fines and has demonstrated the basic principle of the process [32–33].

In the Circofer process, coal and ore are fed into two fluid beds. The first is a circulating fluidized bed where the coal is charred, and the ore is 50-percent metallized. The second is a bubbling fluidized bed where final reduction using the char is achieved. Productivity is limited because of required high retention times in the bubbling fluidized bed. In the proposed combined process for Circofer only the circulating fluidized bed would be used to produce char and a 50-percent metallized product which would be fed into a smelter. Smelting using char could achieve 80-percent post combustion, and final reduction is very rapid [22].

The Circofer process operates at reduction temperatures of approximately 950 °C in a closed gas circuit without producing export gas. One possible application of Circofer is as a single-stage pre-reduction step for the HIsmelt® process (see Fig. 11). It is claimed that this leads to a significant increase in the throughput of the HIsmelt process [33].

The following benefits are reported for Circored and Circofer technology compared to BF production [32–33].

- No iron ore agglomeration required.
- Reduced energy use and CO_2 emissions because sintering process eliminated.
- If Circofer added to the HIsmelt® process, a claimed significant increase in the throughput of the HIsmelt process.

Commercial Status: Circored: Demonstration stage; Circofer: Pilot stage.

3.9. Cyclone converter furnace

In primary iron making, about one-fifth of the energy consumed is used for coke making and sintering. Smelting reduction processes avoid this energy use because they make iron directly from iron ore and coal, omitting the need for coke ovens and sinter plants. The cyclone converter furnace consists of a cyclone for pre-reduction of the iron ore; the cyclone is mounted on a converter-type vessel in which the iron ore is then reduced to iron [20]. The

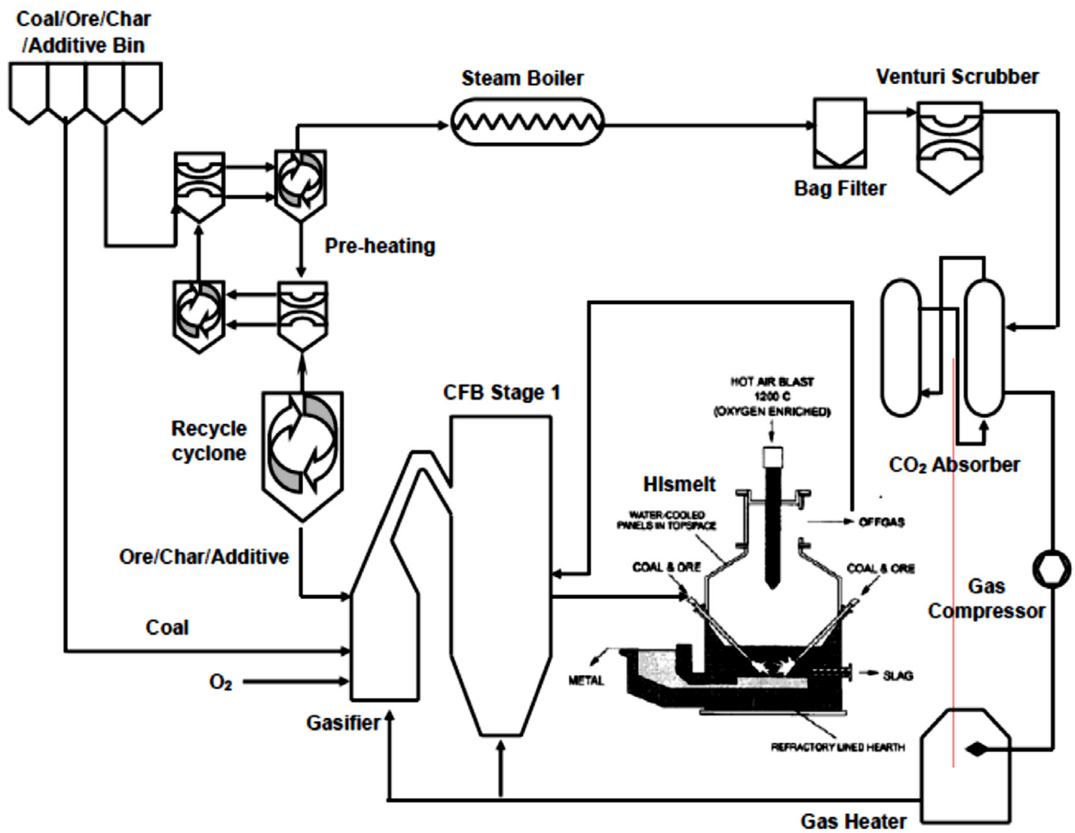


Fig. 11. First-stage Circofer-smelter schematic [22].

iron ore is pre-reduced and melted in the cyclone at the top of the furnace. From there, the molten iron ore falls into the lower part of the vessel where reduction is completed. Granular coal as well as oxygen are introduced in the lower part of vessel. Combining the pre-reduction unit and the final reduction unit avoids heating losses that occur when these two components are separated.

The cyclone converter furnace was the first smelting reduction process that combined pre-reduction and final combustion in one vessel [20]. Currently, its development is included within the HIsarna process [42]

A 20 t/h (h) test facility for the melting cyclone was built and successfully operated in 1994. The converter has not yet been tested on a pilot scale [20]. The cyclone has been implemented in a HIsarna pilot plant which was tested in 2011 [42].

Fig. 12 shows the converter furnace cyclone. The following benefits can be achieved by use of the cyclone converter furnace [9,20].

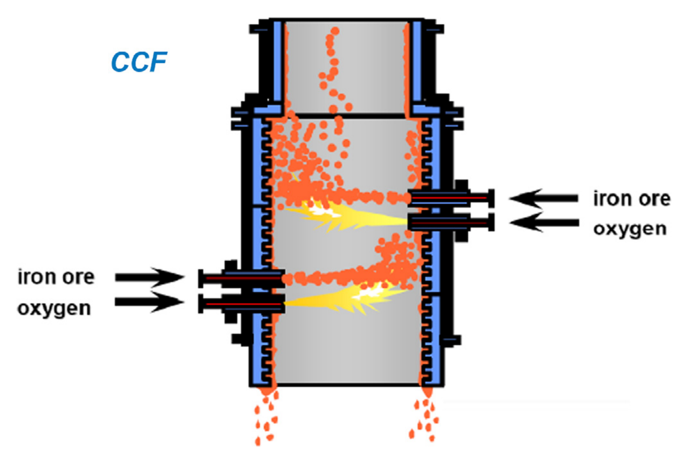


Fig. 12. Converter furnace cyclone (CCF) [42].

- Estimated specific energy consumption of 13–14 GJ/t hot metal (thm) as compared to about 16.1 GJ/thm for the conventional BF production (including coke making and sintering).
- Lower investment costs because the cyclone converter furnace is simple compared to other smelting reduction processes.
- Total production costs estimated to be lower than those of BF.

Commercial status: Pilot stage.

3.10. Producing iron by electrolysis of iron ore (molten oxide electrolysis)

Electrolysis of iron ore or molten oxide electrolysis (MOE) is an emerging process. The DOE/ AISI TR program funded an initial R&D project at MIT (Cambridge, MA USA) which was successfully completed in 2007. A similar technology is currently being studied in the ULCOS program. This process would allow the transformation of iron ore into metal and gaseous oxygen (O_2) using only electrical energy. Producing iron by electrolysis would eliminate the need for coke ovens and the reactors used for reducing the iron ore, such as BFs, and thereby eliminate the CO_2 created by these production methods. Although no iron is currently produced industrially by electrolysis, electrolysis is a well-established technique developed at the industrial scale for production of aluminum, zinc, and nickel [39].

MOE is an extreme form of molten salt electrolysis, a technology that has been used to produce tonnage metal – aluminum, magnesium, lithium, sodium, and the rare-earth metals – for more than 100 years. MOE is different from other molten salt electrolytic technologies because it uses carbon-free anodes, which facilitates the production of oxygen gas at the anode. MOE is totally

carbon-free, producing only O_2, and no CO or CO_2, an environmental advantage compared to conventional technology. Even including the CO_2 emissions from electricity generation related to the process, MOE ranks lowest among breakthrough technologies in terms of CO_2 emissions per unit metal product [13].

The most promising options for electrolysis are ULCOWIN, also called electrowinning, and iron ore ULCOLYSIS (similar to the MIT process). Both technologies have already been demonstrated at a small scale, through the research carried out during ULCOS Phase I.

In the ULCOLYSIS process, iron ore is dissolved in a molten oxide mixture at 1600 °C. This electrolyte medium can sustain a temperature above the melting point of iron metal. The anode, made of a material inert in relation to the oxide mixture, is dipped in this solution. An electric current flows between this anode and a liquid iron pool that is connected to the circuit to act as the cathode. O_2 evolves as a gas at the anode, and iron is produced as a liquid metal at the cathode. The development of ULCOWIN is, however, more advanced. A proposal has been made to further test ULCOWIN through additional scaling up of the process. A prototype plant has been proposed that could produce 5 kg/day [39].

In contrast to a conventional integrated steel mill, which requires coke ovens, BFs, and BOFs, an electrolytic cell reduces iron ore concentrates and produces molten steel in a single unit. Therefore, MOE is expected to have much lower capital costs than a conventional plant. The CO_2 reduction potential is large, depending upon the MOE plant's electricity source. An analysis by Birat in the 1990 s estimated 1750 kg CO_2/t liquid steel from benchmark BF technology compared to 345 kg CO_2/t liquid steel from MOE. This analysis assumed 90 g CO_2/kWh for electric power generation[4] and 3500 kWh/t of molten steel in the electrolytic cell [7].

AISI is funding Massachusetts Institute of Technology to develop and validate scale-up parameters for the design, construction, and operation of a pre-pilot-scale, self-heating MOE cell with a capacity of 4000 A. This cell would operate continuously and produce iron at the rate of about 72 kg/day. If fitted with an inert anode, it could produce about 32 kg of oxygen gas per day. Long-term operation of this cell will provide the data required to design the first-generation industrial-scale cell and develop a detailed cost model to assess the commercial viability of the process [7].

Fig. 13 shows an MOE cell (MIT process) for producing iron. The following benefits are reported for MOE compared to BF production [7,39]

- Significantly lower CO_2 emissions.
- Likely significant capital cost savings.
- Lower level of air pollutant emissions (SO*x*, NO*x*, VOCs) because coke making, BF, and BOF are eliminated.

Commercial status*:* Research/Development stage[5]

3.11. *Suspension hydrogen (or H_2 containing gaseous mixtures) reduction of iron oxide concentrate*

Hydrogen is currently cost prohibitive as a reducing agent or fuel. Large quantities of inexpensive hydrogen may become available in the future based on worldwide R&D work. Hydrogen produces only water vapor and no other gaseous byproducts when used as a reducing agent or fuel [14].

Hydrogen flash smelting would use, as a smelting vessel, a suspension or flash-type furnace similar to those used in the copper industry. Iron ore concentrates would be sprayed directly into the

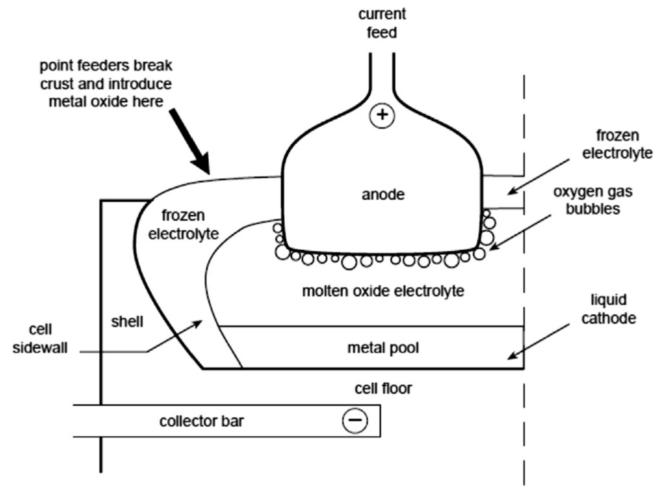


Fig. 13. MOE cell for producing iron [13].

furnace chamber. Three reductants are suitable for this type of vessel: H_2, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics. The high temperature and lack of contact between the iron ore particles in suspension furnaces eliminates sticking and fusion of the particles [7].

Detailed material and energy balances conducted by University of Utah in an earlier R&D project with the support of the DOE/AISI TR Program show that the proposed technology using any of the three possible reductants/fuels could use approximately 38 percent less energy than a BF. This savings results largely from eliminating coke making and the iron ore pelletizing and sintering steps. If hydrogen is used, this new technology will generate only 4 percent of the CO_2 produced in the BF process; when natural gas or coal is used, CO_2 emissions are 39 percent and 69 percent, respectively, of those from a BF. Because the residence time in a suspension furnace is only a few seconds, studies were performed to establish that full reduction could be achieved in such a short time. Kinetic studies of the reduction of iron oxide concentrates ($\sim$30 μm size) as a function of temperature and gas composition showed that 90–99-percent reduction is possible within a few seconds at temperatures of 1300 °C or higher. This was verified by larger bench-scale testing, proving that complete ore reduction is achieved in the residence time typical of industrial-size suspension vessels [7].

Conventional BF-based steelmaking processes use CO gas to remove oxygen in iron ore. However, the molecules of CO gas are large enough that it is difficult for them to penetrate iron ore. By contrast, the much smaller molecules of H_2 gas can easily penetrate into iron ore. The penetration rate of H_2 into iron is five times as great as that of CO, so H_2 can rapidly reduce iron ore in a conventional BF [26].

Hydrogen reduction could be a part of an overall continuous direct steelmaking process, in which case the product from this process would be collected in its molten or solid state (e.g., reduced iron pellets or briquettes) [14].

Based on the success of the earlier project conducted by University of Utah, AISI had initiated a subsequent Phase II-project where a larger-scale bench reactor vessel was fabricated [7]. In 2012, a $7.1 million award was given by the U.S. DOE to AISI/University of Utah to perform tests to determine the best vessel configuration and reductant to be used in a future industrial pilot plant.[6]

[4] This CO_2 emission factor for the electricity is very low. For instance, in 2010, the average CO_2 emission factor of the grid in China was 770 g CO_2/kWh.

[5] The sizes of the prototypes are very small.

[6] Personal communication, Debo Aichbhaumik and Keith Jamison of Energetics, Inc. October 2012.

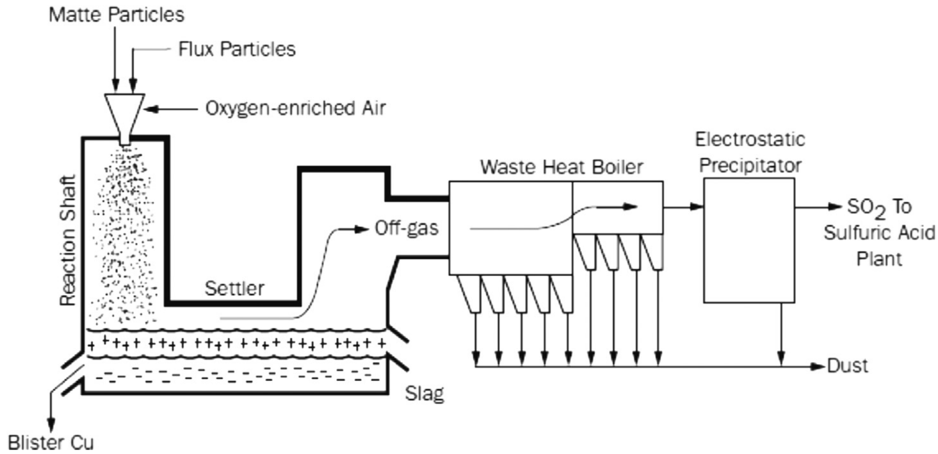


Fig. 14. Hydrogen flash smelting for copper [7].

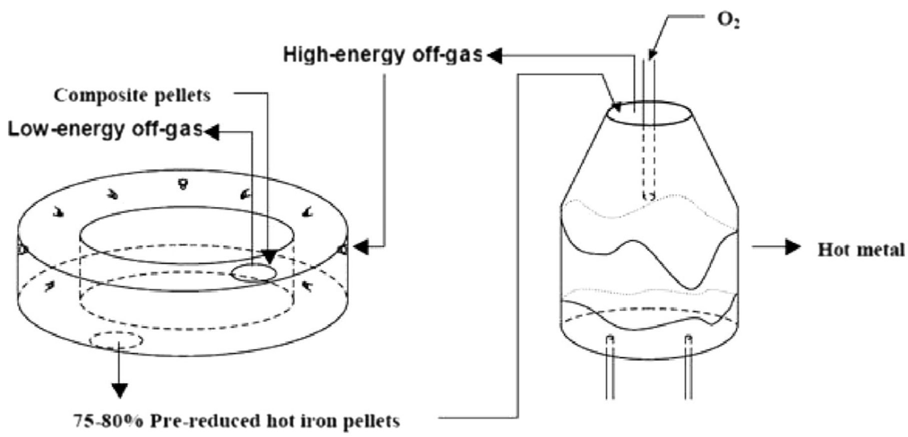


Fig. 15. Schematic of the process proposed for ironmaking using biomass and waste oxides [22].

Fig. 14 is a diagram of hydrogen flash smelting. The following benefits are reported for hydrogen flash smelting compared to BF production [7]:

- Reduction or elimination of CO_2 generation in the ironmaking process.
- Reduction in energy consumption; University of Utah earlier R&D study showed potential energy savings of 7.4 GJ/t hot metal (more than 50 percent of conventional BF energy use).
- Reduction of iron oxide waste.

Commercial status: Research/Development stage.[7]

3.12. Ironmaking using biomass and waste oxides

Ironmaking is the most energy-consuming and therefore CO_2-intense step in the steel industry. Replacing fossil fuels (e.g., coal) with biomass or waste oxide would reduce both energy use and CO_2 emissions. A project funded by the DOE/AISI TR program conducted preliminary research on an ironmaking process using wood charcoal in ore waste pellets (composite pellets) in a RHF. A number of processes are already under development that use composite pellets of ore or waste oxides and a carbonaceous material, such as coal or coke, which are reduced in the solid state using a rotary hearth or similar type of furnace. The product of these processes is too high in gangue and sulfur to be used effectively in the EAF. If biomass is used instead, the metal will be low in sulfur, so further processing in an EAF or a BOF should be possible. It is expected that the reduced iron ore using biomass in composite pellets would contain low percentages of gangue as well [7,15].

The process combines a RHF and a smelter such as the AISI or Direct Iron Smelting Reduction (DIOS) to produce hot metal using wood charcoal in composite pellets (See Fig. 15). In the RHF the reduction of the iron ore is limited to approximately 70–80-percent metallization. The pre-reduced material is then fed into the smelter for final reduction and gangue separation, yielding hot metal. Compared to conventional processes, this process increases RHF productivity and avoids high energy consumption for full metallization in the smelter [23].

So far, no pilot plants have been built, and only computer models have been developed. A computational model predicts productivity gains as high as 50 percent from replacing coal with wood charcoal in the composite pellets [23]. AISI claims the following benefits from using biomass and waste oxides in iron making compared to conventional BF production [15,23]

- Reduction of more than 90 percent in greenhouse gas emissions.
- Significant decrease in capital and operating costs.
- Increased productivity of the rotary hearth furnace.
- Increased recycling of waste oxides in steelmaking.

Commercial status: Research stage.

[7] The sizes of the prototypes are very small.

Table 1
A comparison of ironmaking technologies explained in this paper.

Ironmaking technologies	Reducing agent and energy source				Form of iron ore that can be used				Oxygen is needed	Coal gasification is needed	Commercialization status
	Non-coking Coal	Coke	NG[a]	Other	Sinter	Pellet	lump ore	Fine ore			
Blast furnace		X			X	X					Commercial
COREX® process	X				X	X	X		X		Commercial with very low adoption rate
FINEX® process	X							X	X		Commercial with very low adoption rate
Tecnored	X					X [b]		X [b]			Pilot
ITmk3 ironmaking process	X					X [c]		X [c]			Demonstration
Paired straight hearth furnace	X					X [d]		X [d]			Development
Coal-based HYL process- a syngas based DRI plant	X					X	X			X	Commercial with very low adoption rate
Coal-based MIDREX process	X					X	X		X	X	Demonstration
Fine ore reduction in the circulating fluidized bed (Circored® and Circofer®)	X [e]		X [e]					X			Demonstration/pilot
Cyclone converter furnace	X					X	X		X		Pilot
Producing iron by electrolysis of iron ore (molten oxide electrolysis)				X [f]		X	X				Research/ development
Suspension hydrogen reduction of iron oxide Concentrate			X [g]	X [g]			X	X		X [g]	Research/ development
Ironmaking using Biomass and Waste Oxides				X [h]		X [h]					Research

[a] NG: Natural gas.
[b] Pellets or briquettes used in Tecnored process are made from low-grade iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines which are mixed and agglomerated into pellets or briquettes.
[c] Low grade ores are beneficiated, and the resulting fines (with >62 percent Fe content) are pelletized and used.
[d] Cold-bonded self-reducing pellets composed of iron oxide and coal. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal.
[e] Circored is gas-based (hydrogen as reductant), and Circofer is coal-based.
[f] Only electricity is used.
[g] Three reductants are suitable for this process: H_2, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics.
[h] This process uses wood charcoal in ore waste pellets (composite pellets) in a RHF.

4. Comparison of ironmaking technologies

Table 1 shows a comparison of some of the aspects for different ironmaking technologies explained in this paper with the conventional ironmaking in blast furnace. COREX® Process, FINEX® Process, and Coal-Based HYL Process are very promising alternative emerging ironmaking technologies because they are already commercially proven and are commercialized but they have very low adoption rate in the steel industry worldwide. As can be seen from Table 1, all the alternative emerging ironmaking technologies eliminate energy-intensive coke production.

5. Conclusions

This paper describes 12 alternative emerging energy-efficiency and CO_2 emissions reduction ironmaking technologies for the steel industry. The information presented for each technology was collected from various sources, including manufacturers. All the emerging technologies presented in this paper are alternatives to conventional production of iron. It is likely that no single technology will be the best or only solution but instead that a portfolio of technologies should be developed and deployed to address the increasing energy use and CO_2 emissions of the iron and steel industry.

As can be seen from the information presented in this paper, most of the technologies have not been commercialized yet. Therefore, further research is needed to improve and optimized these technologies in order to make them commercial. In addition, for some technologies, there was not much information available except from the technology developer. Conducting independent studies and validation on the fundamentals, development, and operation of these emerging technologies can be helpful to private and public sectors as well as academia.

Shifting away from conventional processes and products will require a number of developments including: education of producers and consumers; new standards; aggressive research and development to address the issues and barriers confronting emerging technologies; government support and funding for development and deployment of emerging technologies; rules to address the intellectual property issues related to dissemination of new technologies; and financial incentives (e.g., through carbon trading mechanisms) to make emerging low-carbon technologies, which might have a higher initial costs, competitive with the conventional processes and products. It should be noted that the purpose of this paper is solely informational.

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References

[1] International Energy Agency (IEA). Tracking industrial energy efficiency and CO2 emissions. Paris, France; 2007.

[2] (U.S. Geological Survey (USGS). Mineral commodity summaries—iron and steel. Virginia, US; 2012.

[3] Bellevrat E, Menanteau P. Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modeling. Proceedings of the 4th Ulcos seminar; 1–2 October 2008.

[4] Hasanbeigi A, Morrow W, Sathaye J, Masanet E, Xu T. Assessment of energy efficiency improvement and CO_2 emission reduction potentials in the iron and steel industry in China. Report. Berkeley, CA: Lawrence Berkeley National Laboratory Report LBNL–LBNL-5535E; 2012.

[5] Worrell E, Laitner JA, Ruth M, M., Finman H. Productivity benefits of industrial energy efficiency measures. Energy 2003;11(28):1081–98.

[6] Worrell, E, Blinde P, Neelis M, Blomen E., Masanet E. Energy efficiency improvement and cost saving opportunities for the US iron and steel industry: an energy star guide for energy and plant managers; 2010.

[7] (American Iron and Steel Institute (AISI). Technology roadmap research program for the steel industry; 2010.

[8] Asia pacific partnership on clean development and climate (APP). The State-of-the-Art Clean Technologies (SOACT) for steelmaking handbook. (2nd edition); 2010.

[9] European Integrated Pollution Prevention and Control Bureau (EIPPCB). Best Available Techniques (BAT) reference document for iron and steel production industrial emissions directive 2010/75/EU; 2010.

[10] U.S. Environmental Protection Agency (U.S. EPA). Available and emerging technologies for reducing. greenhouse gas emissions from the iron and steel industry; 2010.

[11] U.S. Department of Energy (U.S. DOE)/Advanced Manufacturing Office (AMO). Industries and technologies; 2012. Available from: ⟨http://www1.eere.energy.gov/manufacturing/resources/industries_technologies.html⟩ [accessed January 2014].

[12] Agrawal BB, Mathur AS. New ironmaking processes: relevance to India; 2011 Available from: ⟨http://www.iim-delhi.com/upload_events/01NewIronmakingProcessRelevanceIndia_RDCIS.pdf⟩ [accessed January 2014].

[13] (American Iron and Steel Institute (AISI). Technical feasibility study of steelmaking by molten oxide electrolysis. 2006 TR program book; 2006a, p. 24–5.

[14] (American Iron and Steel Institute (AISI). Suspension hydrogen reduction of iron oxide concentrate. 2006TR program book 2006b, p. 20–1.

[15] (American Iron and Steel Institute (AISI). Evaluation of sustainable steelmaking using biomass and waste oxides. brochure. 2002 TR program book,; 2002 p. 35–6.

[16] Asmet. new pig iron process tecnored technology tested by Vale; September 27, 2011. Available from: ⟨http://www.asmet.com/news/new-pig-iron-process-tecnored-technology-tested-by-vale⟩ [accessed January 2014].

[17] Birat JP. Steel sectoral report–contribution to the UNIDO roadmap on CCS1–fifth draft; 2010.

[18] Danieli Corus. The tecnored process. A new route for producing low cost liquid iron. (n.d.).

[19] Tenova and Danieli. HYL Process Description. (2011) Available at ⟨http://www.energiron.com/default.htm⟩ (Accessed: January 2014).

[20] De Beer J, Blok K, Worrell. E. Future technologies for energy-efficient iron and steelmaking. Annu Rev Energy Environ 1998;23:123–205.

[21] Energetics, Inc. Steel industry—energy bandwidth study; 2004.

[22] Fruehan RJ. Future steelmaking processes: Final Report. United States Department of Energy (U.S. DOE); 2004a.

[23] Fruehan RJ. Sustainable steelmaking using biomass and waste oxides: final technical report. U.S. DOE. Office of Industrial Technologies (OIT); 2004b.

[24] Grill W. The SIMETALCIS corex/finex process. Convention on clean, green and sustainable technologies in iron and steel making;15–17 July, 2009. Bhubaneswar, India.

[25] International Energy Agency (IEA). The Energy Technology Systems Analysis Program (ETSAP)—Technology brief: iron and steel. Paris, 2010.

[26] JISF. COURSE 50—Technologies to reduce CO_2 emissions. 2012. Available from: ⟨http://www.jisf.or.jp/course50/tecnology01/index_en.html⟩ [accessed January 2014].

[27] Lockwood G. Ironmaking process alternatives screening study—volume I: summary report; 2000.

[28] Lu WK. The search for a new ironmaking process towards sustainable development. GCEP industry workshop. Stanford University; April 15–16, 2008.

[29] Mesabi Nugget Delaware. LLC and mining resources, LLC. The Mesabi nugget story; 2011. Available from: ⟨http://www.mesabinuggetmn.com/⟩ [accessed January 2014].

[30] MIDREX Technologies, Inc. Direct reduction–shaft furnace and rotary hearth furnace (RHF); 2012. Available from: ⟨http://www.midrex.com/handler.cfm/cat_id/17/section/technology⟩ [accessed January 2014].

[31] MIDREX Technologies, Inc. MXCOL®: a breakthrough in coal-based direct reduction; 2011. Available from: ⟨http://www.midrex.com/uploads/documents/MXCOL-English%20article%20US.pdf⟩ [accessed January 2014].

[32] Outotec, Inc. Circored® and Circofer®: fine ore reduction in the circulating fluidized bed; 2012. Available from: ⟨http://www.outotec.com/pages/Page.aspx?id=7250&epslanguage=EN⟩ [accessed January 2014].

[33] Outotec, Inc. Fluidization technology; 2007. Available from: ⟨www.outotec.com/36280.epibrw⟩ [accessed January 2014].

[34] Siemens VAI. Competence in ironmaking; 2007. Available from: ⟨www.industry.siemens.com/…/Competence-in-Ironmaking-en.pdf⟩ [accessed January 2014].

[35] SAIL. Press release: SAIL, Kobe steel seal pact to bring environment-friendly steel making to India; 2012. Available from: ⟨http://www.sail.co.in/showpressrelease.php?id=305⟩ [accessed January 2014].

[36] Siemens. Press release: Siemense receives third FINEX order from POSCO; 2011. Available from: ⟨http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2011/industry_solutions/iis201109998.htm⟩ [accessed January 2014].

[37] Tenova HYL. Press release May 2011: JSPL selects energiron for four new DR plants; 2011. Available from: ⟨http://www.tenovagroup.com/pdf/press/60-Jindal%20press%20release.pdf⟩ [accessed January 2014].

[38] Tenova HYL. Improved technologies for cost effective steelmaking. Metal bulletin/Mjunction. Indian steel 2008 conference. Mumbai, India; February 2008.

[39] ULCOS. Alkaline electrolysis; 2012. Available from: ⟨http://www.ulcos.org/en/research/electrolysis.php⟩ [accessed January 2014].

[40] U.S. DOE/Industrial Technologies Program (ITP). Paired straight hearth furnace; 2011.

[41] U.S. DOE/Industrial Technologies Program (ITP). IMPACTS: industrial technologies program: summary of program results for CY 2009; 2010.

[42] van Boggelen J. HIsarna, a low CO_2 ironmaking process. Presentation at Cleveland institution of engineers, Middlesbrough, UK; 2012.

[43] World Steel Association (worldsteel). Steel statistical yearbook 2011; 2011.